

Applic. No.: 09/915,985

Supp. Amdt. Dated August 4, 2004

REMARKS/ARGUMENTS

Reconsideration of the application is requested.

Claims 1 and 3-10 remain in the application. Claim 1 has been amended. Claim 10 has been added.

During a phone conversation with the Examiner on June 15, \_\_\_\_\_ 2004, the Examiner has stated that the "allowed energy levels within said first band gap" is an inherent property of the semiconductor layer and that claim 9 should be incorporated into claim 1.

Applicants do not agree with the Examiner's opinion that the allowed energy states within a band gap is an inherent property of radiation emitting semiconductor materials. In the radiation emitting semiconductor materials, it is basically assumed that the radiation production is linked with a radiating recombination, namely a radiating transition of a charge carrier from the conduction band into the valence band. As an example, Applicants refer to the enclosed textbook "Quantum Electronics," (A. Yariv, 3<sup>rd</sup> Ed.), chapters 11.0 and 11.1 and especially to Fig. 11.1b, which explain this mechanism. The involvement of the allowed energy states

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within the band gap is not necessary for this mechanism and is thus also generally not considered.

If the Examiner were of the opinion that the semiconductor materials in the reality can show to certain extent low percentage states within the band gap due to contaminants, it is determined that, as a rule, the concentration of the contaminants is too low to play a decisive role in the radiation production. The materials based on ZnSe and ZnCdSe named in the instant application present an exception. But, even in these materials, the radiation is basically produced through the radiating transition from the conduction band into the valence band. Allowed energy states within the band gap are not involved in the transition.

However, in order to facilitate the prosecution, the language of claim 1 has been slightly amended to even more clearly show that the invention of the instant application does not call for inherent semiconductor properties. Rather, the semiconductor material of the re-emitting layer is specifically doped to form a component for emitting mixed colors. The support for the change may be found on page 9, lines 11-16 of the specification.

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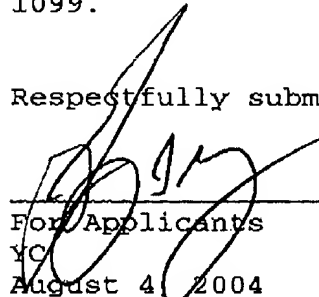
With regard to the Examiner's suggestion to incorporate claim 9 into claim 1, Applicants believe that it is not necessary in consideration of the cited prior art references. However, a separate independent claim 10 has been added, which contains the features of claims 1 and 9.

In view of the foregoing, reconsideration and allowance of claims 1 and 3-10 are solicited.

In the event the Examiner should still find any of the claims to be unpatentable, counsel would appreciate a telephone call so that, if possible, patentable language can be worked out.

If an extension of time for this paper is required, petition for extension is herewith made. Please charge any fees which might be due with respect to 37 CFR Sections 1.16 and 1.17 to the Deposit Account of Lerner and Greenberg, P.A., No. 12-1099.

Respectfully submitted,

  
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August 4, 2004

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# QUANTUM ELECTRONICS

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Third Edition

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JOHN WILEY & SONS

## C H A P T E R 11

## Semiconductor Diode Lasers

## 11.0 INTRODUCTION

Stimulated emission from GaAs semiconductor diode lasers was observed simultaneously by three groups [References 1-3] following theoretical analyses and proposals by Basov et al. and Dunkel (Reference 5).

In the intervening years, the semiconductor diode laser (SDL) has come to dominate the laser field in its technological importance and has become the key element in an increasing number of applications, most notably in optical fiber communication and optical data storage. This "success" is due to the fact that semiconductor lasers are simply pumped by passing a current through them at voltage (and current) levels that are compatible with those of integrated circuits, and because they can be modulated directly at frequencies in excess of 20 GHz (Reference 6). SDL's can be mass-produced by the same photolithographic techniques as electronic circuits and can be integrated monolithically with the latter. This combination has given birth to the field of integrated optoelectronic circuits (Reference 7).

## 11.1 SOME SEMICONDUCTOR BACKGROUND

In this section, we will state some of the more elementary results of semiconductor theory. A detailed treatment of this topic can be found in numerous books dealing with the wave mechanics of solids (References 8 and 9).

The wave function of an electron in a given band (e.g., the valence band) can be written as

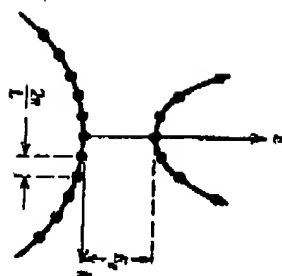
$$\psi_{\mathbf{k}}(\mathbf{r}) = u_{\mathbf{k}}(\mathbf{r})e^{i\mathbf{k}\cdot\mathbf{r}} \quad (11.1-1)$$

where  $u_{\mathbf{k}}(\mathbf{r})$  has the periodicity of the crystalline lattice. The "propagation" constants  $\mathbf{k}$  are quantized in a manner similar to that of (4.2-7) so that we have

$$k_i = \frac{2\pi i}{L_i} \quad (11.1-2)$$

where  $i = x, y, z$ ;  $i$  is an integer and  $L_i$  is the length of the crystal in the  $i$  direction. The volume, in  $\mathbf{k}$  space, per electronic state is thus  $8\pi^3/V$  where  $V = L_x L_y L_z$ . The number of electron states per band with a value of  $k$  between  $k$  and  $k + dk$  is thus given by the volume of a spherical shell of radius  $k$  and

FIGURE 11.1a A typical energy band structure for a direct semiconductor with  $m_v < m_c$ . The uniformly spaced dots correspond to electron states.



thickness  $dk$  divided by the volume per state, that is,

$$\rho(k)dk = \frac{k^3 V}{\pi^2} dk \quad (11.1-3)$$

where a factor of 2 was added to account for the two spin states associated with each  $k$  eigenvalue.

The energy above the band edge associated with a given state  $k$  (e.g., in the conduction band) is

$$E(k) = \frac{\hbar^2 k^2}{2m_c} \quad (11.1-4)$$

in the parabolic band approximation and is thus a function of  $k$  rather than  $k_x$ .  $m_c$  is the effective mass for electrons in the conduction band.  $E(k)$  is measured from the bottom of the band.

Figure 11.1a shows a typical energy band structure  $E$  versus  $k$  for a direct semiconductor, that is, for a semiconductor in which the conduction band minimum and the valence band maximum occur at the same point in  $\mathbf{k}$  ( $k_x, k_y, k_z$ ) space. The direction of  $k$  must be specified in general except in the parabolic band approximation. The black dots correspond to allowed energy states and are spaced uniformly in  $k$ . According to (11.1-4), the situation depicted by Figure 11.1a corresponds to  $m_v > m_c$ .

From the expression for the density of states in  $\mathbf{k}$  space (11.1-3) and from (11.1-4), we obtain readily the expression for the density of states per unit energy interval

$$\rho_c(E) = \frac{1}{V} \rho_c(k) \frac{dk}{dE} = \frac{1}{2\pi^2} \left( \frac{2m_c}{\hbar^2} \right)^{3/2} E^{1/2} \quad (11.1-5)$$

where the subscripts  $c$  and  $v$  refer to the conduction and valence bands, respectively, and where the energy  $E$  is measured from the band edge extreme.

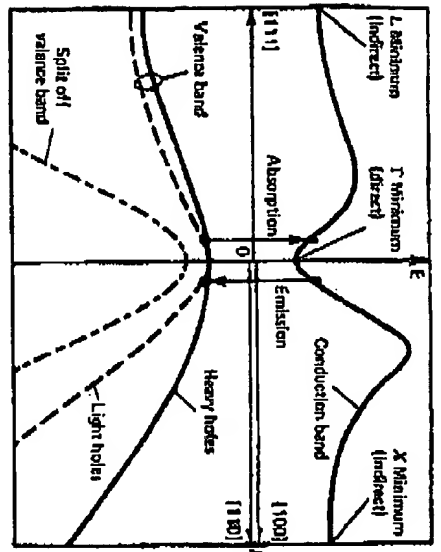


FIGURE 11.1b Plot of energy versus wave-vector for electrons in conduction and valence bands of direct-gap semiconductor, for example, GaAs (diagrammatic). Source: Reference 10.

num. The actual energy diagram of GaAs near  $k = 0$  is shown in Figure 11.1b.

### The Fermi-Dirac Distribution Law

The probability that an electron state at energy  $E$  is occupied by an electron is given by the Fermi-Dirac law

$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1} \quad (11.1-6)$$

where  $E_F$  is the Fermi energy and  $T$  the temperature. In thermal equilibrium, a single Fermi energy applies to both the valence and conduction bands. Under conditions in which the thermal equilibrium is disturbed, such as in a  $p-n$  junction with a current flow or a bulk semiconductor, in which a large population of conduction electrons and holes is created by photoexcitation, separate Fermi levels  $E_F$  and  $E_{Fh}$ , called quasi-Fermi levels, are used for each of the bands. The concept of quasi-Fermi levels in excited systems is valid whenever the carrier scattering time within a band is much shorter than the equilibrium time between bands. This is usually true at the large carrier densities used in  $p-n$  junction lasers.

A good estimate of the Fermi level  $E_F$  can be obtained by deriving its value at  $T = 0$ . In this case, it follows from (11.1-6) that all the energy levels up to  $E_F$  are occupied and those above it are empty. In this case, we obtain from (11.1-5)

$$N = \int_0^{E_F} \rho(E) dE = \frac{1}{2\pi^2} \left( \frac{2m_e}{\hbar^2} \right)^{3/2} \int_0^{E_F} E^{1/2} dE$$

where  $N$  is the density of electrons (of all energies) in the conduction band.

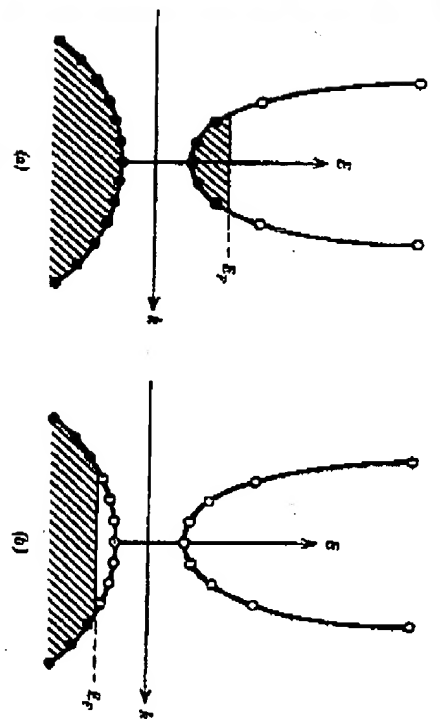


FIGURE 11.2 (a) Energy band of degenerate  $n$ -type of semiconductor at 0 K. (b) A degenerate  $p$ -type of semiconductor at 0 K. The cross hatching represents regions in which all the electron states are filled. Empty circles indicate unoccupied states.

Carrying out the integration gives

$$E_F = \frac{\hbar^2}{2m_e} \left( \frac{3\pi^2 N}{v} \right)^{2/3} \quad (11.1-6a)$$

In very highly doped semiconductor, the Fermi level is forced into either (a) the conduction band for donor impurity doping or (b) into the valence band for acceptor impurity doping. The semiconductor is said to be degenerate. This situation is demonstrated by Figure 11.2. According to (11.1-6) at 0 K, all the states below  $E_F$  are filled, whereas those above it are unoccupied as shown in the figure. In this respect, the degenerate semiconductor behaves like a metal where the conductivity does not disappear at low temperatures. The unoccupied states in the valence band are referred to as "holes," and they are treated like the electrons except that their charge, corresponding to an electron deficiency, is positive and their energy is measured downward.

### The Reciprocal Lattice Expansion

In a crystal with primitive translation vectors  $a, b, c$ , which threesome determines the primitive unit cell, we can define three reciprocal lattice vectors

$$A = \frac{2\pi b \times c}{a \cdot b \times c}, \quad B = \frac{2\pi c \times a}{a \cdot b \times c}, \quad C = \frac{2\pi a \times b}{a \cdot b \times c} \quad (11.1-7)$$

so that

$$\begin{aligned} a \cdot B &= a \cdot C = 0, & a \cdot A &= 2\pi \\ b \cdot A &= b \cdot C = 0, & b \cdot B &= 2\pi \\ c \cdot A &= c \cdot B = 0, & c \cdot C &= 2\pi \end{aligned} \quad (11.1-8)$$

The set of points in the real lattice that can be reached by

$$\rho(h, k, l) = ha + kb + lc \quad (11.1-9)$$

where  $h, k, l$  are any integers are all equivalent. Similarly, a vector in the reciprocal lattice can be defined by any triplet of integers, say  $m, n, p$

$$G(m, n, p) = ma + nb + pc \quad (11.1-10)$$

so that from (11.1-8)

$$G(m, n, p) \cdot \rho(h, k, l) = \{mh + nk + pl\}2\pi \exp iG(m, n, p) \cdot \rho(h, k, l) = 1 \quad (11.1-11)$$

Any function that possesses the same periodicity as that of the crystal lattice can be expanded as

$$f(r) = \sum_G a_G e^{iG \cdot r} \quad (11.1-12)$$

where  $G = G(m, n, p)$ . This can be verified by expanding

$$f(r + \rho(h, k, l)) = \sum_G a_G e^{iG \cdot (r + \rho)} = f(r) \quad (11.1-13)$$

where the last equality follows from (11.1-11)

## 11.2 OPTICALLY INDUCED BAND-TO-BAND TRANSITIONS IN SEMICONDUCTORS

The interaction Hamiltonian of an electron with an electromagnetic field will be taken as

$$H' = -\frac{e}{m} \mathbf{A} \cdot \mathbf{p} \quad (11.2-1a)$$

where  $\mathbf{A}(r, t)$  is the vector potential of the optical field as discussed in Section (5.1) and  $\mathbf{p}$  is the electron momentum operator.

It can be shown, the proof being assigned as a problem, that in a periodic crystal we can also express  $H'$  by

$$H' = -e\mathbf{E} \cdot \mathbf{r} \quad (11.2-1b)$$

where  $\mathbf{E}$  is the electric field.

We assume an "x" polarized optical field

$$\mathbf{A}(r, t) = \hat{x} \frac{A_0}{2} e^{i(j\omega t - k_{\text{opt}} \cdot r)} \quad (11.2-2)$$

so that

$$H' = i\hbar \frac{eA_0}{2m} e^{-i(j\omega t - k_{\text{opt}} \cdot r)} \frac{\partial}{\partial x} + \text{Hermitian Adjoint}$$

The induced transition rate of an electron from the conduction to the

valence band, or in reverse, will thus involve the matrix element

$$H'_{\alpha\beta} \propto \int_{\text{crystal}} u_{\beta}^* e^{-i(k' + k_{\text{opt}}) \cdot r} \frac{\partial}{\partial x} \left( u_{\alpha} e^{i(k + k_{\text{opt}}) \cdot r} \right) d\tau \quad (11.2-2)$$

Since  $u_{\alpha}$  and  $u_{\beta}$  are periodic, we can expand them according to (11.1-12)

$$u_{\alpha} = \sum_G a_{\alpha G} e^{iG \cdot r} \\ u_{\beta} = \sum_G a_{\beta G} e^{iG \cdot r}$$

so that

$$H'_{\alpha\beta} \propto \sum_G \sum_{G'} a_{\alpha G} a_{\beta G'} \int_{\text{crystal}} \exp[i(-k - k_{\text{opt}} + k' - G + G') \cdot r] d\tau \quad (11.2-3)$$

We can express the position  $\mathbf{r}$  with the unit cell

$$\mathbf{r} = \rho(h, k, l) + \delta\mathbf{r}$$

so that  $\delta\mathbf{r}$  is the position relative to the "address"  $\rho(h, k, l)$  of the unit cell  $h, k, l$ . The integral in (11.2-3) can then be expressed as

$$\sum_{h,k,l} \int_{\text{unit cell}(h,k,l)} \exp[i(-k - k_{\text{opt}} + k' - G + G') \cdot (\rho(h, k, l) + \delta\mathbf{r})] d\tau \\ = \int_{\text{any unit cell}} \exp[i(-k - k_{\text{opt}} + k' - G + G') \cdot \delta\mathbf{r}] d\tau \sum_{h,k,l} \exp[i(-k - k_{\text{opt}} + k') \cdot \rho(h, k, l)]$$

The last summation, in general, amounts to adding up complex phases with arbitrary phases, a procedure leading to a "small" number unless

$$\mathbf{k}' = \mathbf{k} + \mathbf{k}_{\text{opt}} \quad (11.2-4)$$

in which case, the summation is equal to the number of unit cells in the crystal.

Since, in general,  $k_{\text{opt}} \sim 10^5 \text{ cm}^{-1}$  while  $k, k' \sim 10^6 - 10^7 \text{ cm}^{-1}$ , except at the very bottom of the bands, we neglect  $k_{\text{opt}}$  in (11.2-4) and write

$$\mathbf{k}' = \mathbf{k} \quad (11.2-5)$$

as a necessary condition for optical transitions in a semiconductor.

### Optical Gain and Loss in Semiconductor Media

We are now in a position to treat the problem of absorption or gain in a semiconductor. Consider the transition between the states (a) and (b) shown in Figure 11.3. The transition conserves "momentum" and is represented in Figure 11.3 by a vertical arrow. The sample is assumed to be in thermal